THE FORMATION OF ICE AND THE GRAINED STRUCTURE OF GLACIERS.[1]

In the following pages I have the honour to lay before the Royal Society the results of a lengthy research on the formation of ice and the grained structure of glaciers, which may serve as a complement to the previous investigations on the same subject published in the *Philosophical Transactions* and *Proceedings of the Royal Society* by Forbes, Tyndall and Huxley, Tyndall, Faraday, T. Graham, J. F. Main, J. C. McConnel, and D. A. Kidd, and elsewhere by Guyot, Agassiz, James Thomson, and Sir William Thomson (now Lord Kelvin), Hermann and Adolf Schlagintweit, Person, Leydolt, Rüdorff, Bertin, Grad, and A. Dupré, Moseley, A. Heim, J. T. Bottomley, K. R. Koch and Klocke, Forel, Ed. Hagenbach-Bischoff, E. von Drygalski, Mügge, H. Hess, and others.

(1) It will be convenient at the outset to define the precise meaning with which it is proposed to employ certain words, some of which are in vague popular use, while others are less familiar, or new.

By an *oily* liquid will be meant one which has surface tension in the common surface with other liquids with which it may be in contact. According to this definition a solution of any salt will, in comparison with pure water or a weaker salt solution, be called, in certain circumstances, an oily liquid.

An *emulsion* is a watery liquid containing suspended drops of oily liquid, or drops of any sort enclosed in an oily skin. These drops can coalesce into larger drops, or the oily skins can join on to one another, and form a continuous mass of bubbles, or foam. Thus *foam* consists of portions of watery liquid enclosed in, and separated from one another by adjacent partitions of oily liquid. Each space thus enclosed will be called a *foam-cell,* and the enclosing partition the foam-wall. If the foam-cells are very small, and the fluid foam-walls very thin (or invisible), the whole is then a *liquid jelly*. The jelly is stiff, the foam stiff or solid, when the walls or the contents of the foam-cells, or both, have become solid.

"*Nearly pure*" applied to water or ice will be used in the special sense of "containing only very small amounts of any salt." *Salt* itself is used throughout in the general chemical sense, that is, not restricted to sodium chloride.

(2) I have allowed pure water, and water containing dissolved salt, to freeze in the dark at various rates, and to melt away slowly in the dark, in open air, and in sunlight. The ice prisms employed were from 1 mm. to 1000 mm. thick, and as the thawing proceeded their various layers were systematically examined—sometimes for days together—with the naked eye, with the microscope, and with polarised light. The same appearances presented themselves in the same order as those which for thirty-seven years past I have investigated and described in solutions of silicic acid, glue, or other colloids, when these are evaporated to form gelatinous masses or thin films, and develop fissures. I have shown that thin viscous oily films of more concentrated solution exist in a less concentrated solution of the same substance, and form folds, straight and twisted tubes, cylinders or cones, spheres and bubbles, open and closed foam-cells with visible and invisible foam-walls. Thin solid films behave like films of very viscous liquid. Whether the oily films form tubes or bubbles and foam-cells joining on to one another depends on the viscosity of the oily liquid. The mutual inclination of the foam-walls, and their surface tensions, continually change as the concentration of the oily liquid changes, and in the case of invisible foam-walls may depend also on the thickness of the oily film. When the oily film is very thin, its surface tension diminishes with diminishing thickness of the film. Oily foam-walls that are formed against solid surfaces are normal to these surfaces. If three oily foam-walls meet in a common edge at equal angles of 120°, they have equal surface tensions.

The foam-cells of a liquid jelly immersed in water can increase or diminish in volume by the diffusion of water through the foam-wall inwards or outwards, *i.e.* the liquid jelly can *swell* or *shrink*. Two clots of liquid jelly can coalesce into one, which does not occur with clots of solid jelly, nor can these latter swell or shrink.

A liquid jelly becomes for the time being positively or negatively doubly refracting when the viscous walls, or the viscous contents of the foam-cells, are expanded or compressed. A jelly remains permanently doubly refracting when the walls or the contents of the foam-chambers solidify while in an expanded condition.

(3) Now, ice is a liquid jelly, with foam-walls of concentrated "oily" salt solution, which enclose foam-cells containing viscous, doubly refracting, pure or nearly pure water.

(4) The further the temperature falls below 0°, the greater is the viscosity of both liquids—in the walls and in the interior of the foam-cells—and the less the plasticity of the ice.

(5) At very low temperatures, the ice breaks with conchoidal fracture at the surface of the invisible spherical foam-walls, which as the whole cools have contracted differently from their contents.

(6) The "glacier grains" are foam-cells filled with pure or nearly pure ice, and separated from one another by visible or invisible walls of oily salt solution.

(7) The union of two pieces of ice under water ("regelation"), and the increase in size of the glacier grains as they approach the lower end of the glacier, correspond to the running together of two gelatinous clots (of silicic acid, or glue) containing liquid foam-cells and liquid cell-contents. At the same time the oily foam-walls between the glacier grains become thicker, and then get thinner again through the draining away of the liquid salt solution at the foot of the glacier.

(8) All water, even the purest, contains traces of salt. As the water cools, ice crystals and oily mother liquor separate at short intervals, or periodically. Under the influence of the surface tension, the oily salt solution forms invisible foam-walls, the surface-tension of which decreases as the thickness of the walls and the concentration of the salt solution diminish. Otherwise, as the cooling proceeds, the salt solution becomes continually more concentrated, and the wall thinner. Finally, the concentrated salt solution also freezes to ice and solid salt. The value of the surface tension determines the angles at which three walls meet in a common edge. If three foam-walls meet at equal angles of 120°, the three walls have equal surface tensions, whereas an inclination of 90° means that fluid foam-walls have been formed in contact with old and already solidified ones.

(9) When water containing air freezes, the air, like the salts dissolved in the water, separates out at short intervals, or periodically. The white places in ice, which are those containing these air bubbles, are also the richest in salt.

(10) As water containing salt, but free from air, cools, the periodical separation of ice and salt gives rise, alike in sea ice, in artificial ice, and in glacier ice, to layers of ice containing varying amounts of salt. By pressure or by absorption of radiation (sunlight, electric light, or daylight), the parts of the ice which are rich in salt melt sooner than pure ice.

(11) In sunlight or electric light furrows are formed at the places rich in salt on the surface of sea ice, artificial ice, and glacier ice. (Forel's stripes; Forbes's "dirt bands"; foam-walls of the great foam-cells of the Kjendal Glacier.)

(12) The salt solution formed in sea ice, artificial ice, or glacier ice, through pressure or sunshine, shows, by the hollows which it fills, the forms assumed under the influence of the surface tension by the boundary between the oily salt solution and the water, just before the freezing of the water. As the ice melts, it contracts. Thus in sea ice pressure or absorption of heat radiation causes the formation, in horizontal layers parallel to the frozen surface, of Tyndall's liquefaction figures, vacuous bubbles, ice flowers, and "fir trees" with branches meeting at 120° and 90°, just like those obtained when colloid solutions are evaporated to dryness, or when salt solutions are allowed to crystallise.

In the case of artificial ice which has been frozen in deep prismatic troughs, these liquefaction figures are formed in the diagonal and median planes of the ice block, which were the last parts to freeze, and where the mother liquor had accumulated.

[1] By Prof. G. Quincke, For.Mem.R.S. Paper received at the Royal Society on June 19.

(13) Sea ice and artificial ice break up in sunlight into little hexagonal prisms of clear ice. These suffer mutual displacement the less easily, the thinner are the fine foam-walls (which have now melted again, and which, when the freezing took place, were formed out of oily salt solution, normal to the surface), and the less salt the water contained before freezing.

The purer the water was, the larger are these hexagonal prisms or foam-cells.

(14) The capillary fissures in transparent glacier ice are these fine foam-walls of oily salt solution.

(15) When water containing little salt freezes in deep metal troughs surrounded with strongly cooled brine, the oily salt solution separates in thin layers normal to the surface, and forms bubbles, foam-cells clinging to one another, or—when the oily liquid at low temperatures is very viscous—folds or hollow pipes, which are filled with pure or nearly pure ice, or with air if such were present in the water. The artificial ice is seen to be traversed by many horizontal tubes, normal to the surface, which are specially numerous in the diagonal and median planes of the ice block, where the mother liquor had accumulated. The less salt is contained in the ice, the more transparent are these diagonal and median planes of the artificial ice block.

Illumination with sunlight or daylight causes the appearance of fresh tubes. The ice becomes more cloudy, and subsequently more transparent again.

(16) When water containing air freezes in deep metal troughs, the upper part of the ice block shows horizontal layers consisting alternately of transparent pure ice and of opaque salt-containing ice with numerous air bubbles. The more salt the water contains, the more numerous and the closer are the opaque layers. In sunlight these opaque layers melt more easily than the transparent ones, and furrows are formed on the surface of the opaque ice.

(17) If the ice is allowed to thaw again in a warm room, or is exposed to radiation (daylight), the parts rich in salt melt sooner than those which contain little salt. The tubes of oily salt solution bulge and coil up, and then break up with contraction of volume into spherical bubbles, which may be vacuous or filled with air. The foam-cells exhibit shapes like those of colloids and jellies as they swell or shrink, or those tree-like and branched formations which I have described in the case of the "liquid precipitates" of metallic silicates and cyanides. If the capillary fissures in this opaque ice are filled with very viscous salt solution, or if the oily salt solution forms no continuous foam-cells, it cannot run away. The ice remains white, as glacier ice actually does.

(18) When an ice block thaws under the long-continued action of daylight, there appear, in the diagonal and median planes of the block, bright bands and cloudy bands, which change their shape and position as the duration and intensity of the radiation alter. This is due to the formation of new foam-walls of oily salt solution and the disappearance of old ones. The angles between the foam-walls are also seen to change, which means that the surface tension of these walls is changing. Now as the amount of salt in the diagonal planes increases, and the absorbed radiation diminishes, towards the interior of the ice, and as further the surface tension and viscosity alter with changing concentration and temperature, it follows that the shapes assumed by the oily layers in the interior of the ice under the influence of the surface tension also undergo change.

(19) After thirty to thirty-six hours, the block of artificial ice had melted in the warm room to half its original height (1 metre), and at the foot and warmer places had given way in a pasty mass. In the upper portion, foam-walls had formed in the pure ice, inclined 120° to one another. In these, as in the median layer that had thawed away, melting salt solution ran down for hours. At the warmer places, and at the thin uppermost crust, glacier grains were formed. These were foam-cells, 5 mm. to 10 mm. wide, filled with doubly refracting ice, and separated from one another by singly refracting foam-walls of transparent salt solution. At the junctions of the foam-walls there often lay tetrahedra, bounded by spherical surfaces and filled with transparent liquid.

(20) In the diagonal and median planes of a block of artificial ice (1 metre high) containing a certain very small amount of salt, and exposed to a certain intensity of radiation, there can be formed horizontal closed tubes of pure or nearly pure ice, having rounded heads and sides bulging at places, and filled with liquid salt solution. They slowly swell, slowly break up into separate bubbles, and then slowly pass away. They are first formed low down, at places of high pressure, and afterwards higher up, at places of low pressure.

(21) When distilled water, free from air, was frozen in iron troughs, it was found at a certain temperature or with a certain concentration of the salt solution and the oily foam-wall that the walls and contents of the closed tubes in the lower part of the median plane were for some time coloured yellow. Subsequently this colour disappeared. It was not present when the water was frozen in brass troughs. I believe it was due to ferric oxide, which was differently soluble in the walls and in the liquid inside the foam-cells, and at a higher temperature became insoluble and sank to the bottom.

(22) The phenomena of melting ice depend both on the velocity of freezing and the velocity of thawing. The more rapidly the water freezes, the more numerous are the foam-walls, and the smaller the foam-cells.

(23) Very dilute solutions of different salts, when slowly frozen under similar conditions, give oily layers of varying viscosity and surface tension, or spheres, bubbles, tubes, and foam-walls of varying form. I have shown this with freshly boiled water containing 0·000003 per cent. of NaCl, or equivalent quantities of KCl, K_2CO_3, Na_2SO_4, $CaCl_2$, $MgCl_2$, $Al_2(SO_4)_3$. The water was frozen in prismatic troughs of brass or tin.

(24) During the freezing of water containing 0·0015 per cent. of Na_2SO_4, and also containing air, the air separated at the same time as the mother liquor. The bounding surface between air and almost solidified, very viscous liquid, tends to become as small as possible, and rolls up together to form hollow cylinders, the radii of which are the smaller the more quickly the ice has frozen. The water freezes the more slowly the further it is from the strongly cooled (below 0°) side of the trough. The thin layers forming the walls of the tubes are normal to the solid surface of the side of the trough, or of the transparent mantle of ice which encloses the mother liquor. They frequently form cylindrical or conical tubes, 6 mm. to 12 mm. long, with a whitish skin, and filled with air. Their axes are normal to the surface, and their pointed ends are directed towards the outer side of the ice mantle. At the base of the tubes, which may be 0·5 mm. to 2 mm. wide, there hangs a whitish hollow sphere inside the mother liquor.

(25) On slowly freezing water containing from 0·00014 per cent. to 0·0014 per cent. of Na_2SO_4, or 0·003 per cent. of NaCl, it happens at times that the mother liquor, which is surrounded by a transparent mantle of ice, contains numerous flat crystalline plates of pure ice. These, by their shape, position, and inclination to one another, clearly show that they have been formed from thin oily foam-walls of pure water, which, as the cooling proceeded, have separated from the watery salt solution, and then solidified.

(26) When a test tube, containing boiling distilled water, is plunged into liquid air, the water freezes very quickly to a milky-white mass of ice, with fissures normal to the surface of the glass. If the test-tube with the white ice—the whole being now cooled down to −190°—is plunged into distilled water, it becomes coated on the outside with a thin crust of ice, which can be detached with a knife, and examined in a watch-glass under the polarising microscope. It consists of small glacier grains or foam-cells (0·1 mm. to 0·2 mm. in diameter) the flat walls of which are normal to the cylindrical surface, and are inclined to one another at angles of 120°, 110°, and so on. The interior of each foam-cell contains a crystal of ice, which in the different cells is differently orientated. When the ice in the test-tube is crushed with a steel point, it exhibits a fibrous fracture, with fine fibres normal to the cylindrical surface. Occasionally in the cross-section are seen concentric cylinders composed alternately of transparent and of white ice. The latent heat of the slowly freezing water diminishes the loss of heat, and the velocity of cooling changes. The ice in the transparent layers was frozen

slowly, that in the opaque ones quickly. As this ice thaws in a watch-glass under the polarising microscope, the lumps of quickly frozen white ice exhibit immense numbers of strings—arranged radially alongside one another—of spheres and lenticular masses, 0·01 mm. to 0·02 mm. in thickness, consisting of very nearly pure water. In each sphere there was a vacuous bubble 0·0006 mm. in diameter.

(27) Slowly frozen water showed, on thawing, similar strings of (liquid) spheres and lenticular masses (of larger size, viz. 0·04 mm. to 0·12 mm. diameter), normal to the surface of the block of ice. These spheres and lens-shaped masses had been formed out of solid or hollow cylinders, or long thin cones with local swellings or bulgings. Frequently lens-shaped masses bounded by two spherical surfaces lay in a thin, flat, spiral or warped foam-wall.

(28) The fibres and cylindrical or conical tubes, like the tubes filled with air, were formed out of thin layers of very viscous, oily liquid, which, as the cooling proceeded, separated out, normal to the surface, and under the influence of the surface tension rolled up, being unable, by reason of excessive viscosity, to form spheres or bubbles.

(29) When the thawing has gone on for a long time, fewer foam-walls and larger foam-cells, or glacier grains, appear in the lumps of ice. The strings of liquid spheres, normal to the surface, show an increase in the size of the spheres, caused by the coalescence of the small spheres in the doubly refracting mass of ice into larger ones. An increased amount of salt in the ice assists this coalescence. The tubes or strings of spheres could often be followed continuously through several glacier grains. The partition walls of the glacier grains, when illuminated, often show hundreds of small lens-shaped masses of the same or gradually diminishing size.

(30) By repeated fractional freezing and melting of the ice crystals formed, continually purer and purer ice is obtained, with increasingly large foam-cells or glacier grains. I have, however, not yet succeeded, even by repeated slow freezing, in obtaining ice free from foam-walls or from glacier grains.

(31) A block of transparent ice was cut through, as described by Bottomley, with a loaded wire loop. The loop was of steel wire, or of platinum wire previously heated to redness, and carried 2 kilograms or more. In no case was the plane of section transparent, but always opaque from the presence of solidified foam bubbles of oily salt solution, possessing refracting power different from that of their surroundings.

(32) Each separate glacier grain in artificial ice contains a differently orientated crystal of ice, the optic axis of which is very seldom normal to the surface of the ice. When in natural sea ice the optic axes of the separate crystals in the different grains are found to be normal or parallel to the free surface of the water, the separation of orientated crystals of ice may have been started by the contact-action of ice crystals or snow flakes falling on the surface of the super-cooled water, and swimming thereon in a horizontal position.

(33) The more slowly artificial ice has frozen, and the less salt it contains, the more transparent, rigid, and difficult to cut with a knife it is.

(34) Every block of artificial ice cleaves, on pressure with a steel point, along the diagonal and median planes, in which, as the ice crystals separated out on freezing, the mother liquor became more concentrated through holding the traces of salt dissolved in a continually diminishing volume of liquid.

(35) The planes of easiest cleavage in natural ice crystals (laminated structure, displacement without bending) are due to invisible layers of liquid salt solution which are embedded in the crystals, normal to the optic axis, or often in other positions.

(36) Ice crystals at temperatures below 0° consist of doubly refracting viscous liquid, and are intermediate between the soft crystals of serum albumen and ordinary crystals of quartz, felspar, &c.

(37) At the edge of Tyndall's liquefaction figures, while they are in process of enlarging, or on the bursting of the foam-walls of artificial ice as it melts, one often sees periodic vortex movements. These arise from a periodic capillary spreading out ("Ausbreitung") of the salt solution of the foam-walls at the boundary between pure water and air or vacuum.

(38) Tyndall and Huxley observed in white glacier ice transparent lenticular masses bounded by spherical surfaces. These were foam bubbles of water free from air, which were enclosed in a thin skin of oily salt solution and had solidified while embedded in such a skin.

(39) The blue bands in glacier ice consist of pure ice, while the white bands are composed of ice containing salt and air bubbles. They are formed by the periodical action of solar radiation and by changing pressure, or by the slow descent of the portions rich in salt, or by the slow ascent of air bubbles in the viscous liquid of the glacier ice.

(40) The ice of the snow flakes which fall on the upper part of the glacier becomes fertilised with inorganic salts derived from disintegrated rocks, and is, as it were, hatched out by the sun's rays, forming "névé" or "firn" snow and glacier grains, or foam-cells filled with ice in the glacier proper. The glacier ice travels on, rolling (or "wallowing") slowly downwards as a living river of ice. Its skeleton of liquid salt solution changes the while, and forms new and larger foam-cells, which, at the lower end of the glacier, perish, disappear, and flow away as the water of the glacier stream.

THE BRITISH ASSOCIATION.

SECTION L.

EDUCATIONAL SCIENCE.

OPENING ADDRESS BY SIR RICHARD C. JEBB, LITT.D., D.C.L., M.P., PRESIDENT OF THE SECTION.

University Education and National Life.

EVERY country has educational problems of its own, intimately dependent on its social and economic conditions. The progressive study of education tends, indeed, towards a certain amount of general agreement on principles. But the crucial difficulties in framing and administering educational measures are very largely difficulties of detail; since an educational system, if it is to be workable, must be more or less accurately adjusted to all the complex circumstances of a given community. As one of those who are now visiting South Africa for the first time, I feel that what I bring with me from England is an interest in education, and some acquaintance with certain phases of it in the United Kingdom; but with regard to the inner nature of the educational questions which are now before this country, I am here to learn from those who can speak with knowledge. In this respect the British Association is doing for me very much what a famous bequest does for those young men whom it sends to Oxford; I am, in fact, a sort of Rhodes scholar from the other end—not subject, happily, to an age limit—who will find here a delightful and instructive opportunity of enlarging his outlook on the world, and more particularly on the field of education.

As usage prescribes that the work of this Section, as of others, should be opened by an Address from the Chair, I have ventured to take a subject suggested by one of the most striking phenomena of our time—the growing importance of that part which Universities seem destined to play in the life of nations.

Among the developments of British intellectual life which marked the Victorian age, none was more remarkable, and none is more important to-day, than the rapid extension of a demand for University education, and the great increase in the number of institutions which supply it. In the year 1832 Oxford and Cambridge were the only Universities south of the Tweed, and their position was then far from satisfactory. Their range of studies was too narrow; their social operation was too limited. Then, by successive reforms, the quality of their teaching was improved, and its scope greatly enlarged; their doors were opened to classes of the community against which they had formerly been closed. But meanwhile the growing desire for higher education—a result of the gradual improvement in elementary and secondary training—was creating new